

Jan. 10, 1967

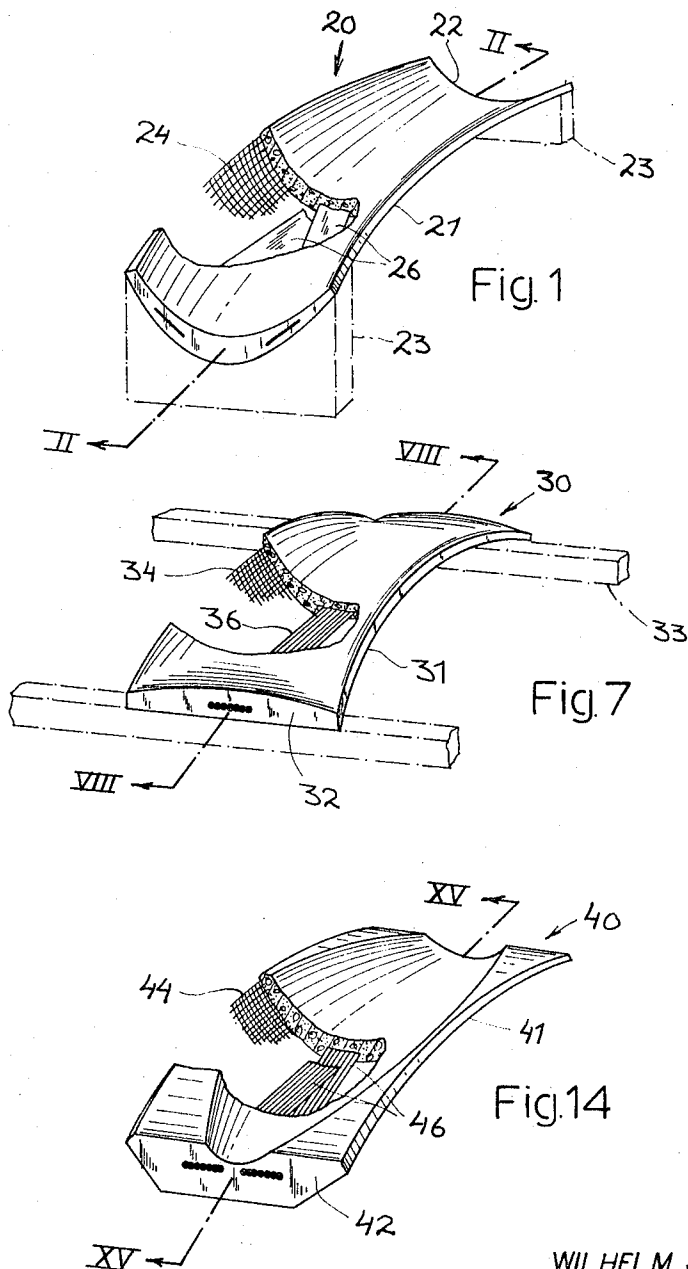
W. J. SILBERKUHL ET AL

3,296,754

SHELL STRUCTURE FOR CONCRETE CONSTRUCTION

Filed Nov. 22, 1963

4 Sheets-Sheet 1



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SHELL STRUCTURE FOR CONCRETE CONSTRUCTION

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4 Sheets-Sheet 2

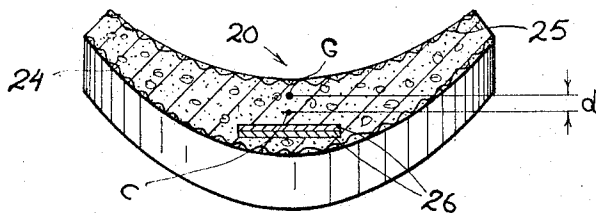


Fig. 4

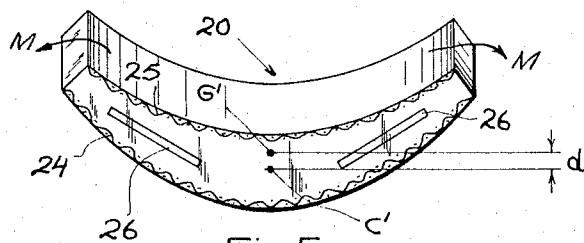


Fig. 5

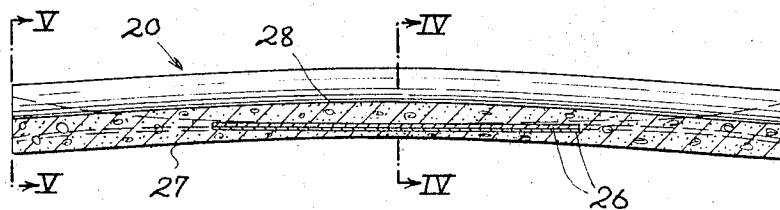


Fig. 2

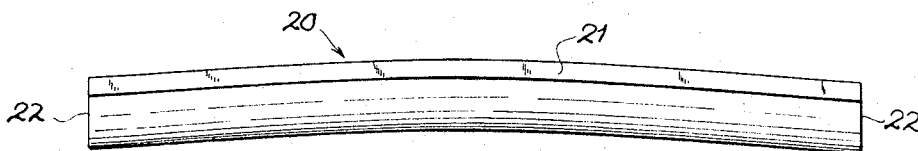


Fig. 3

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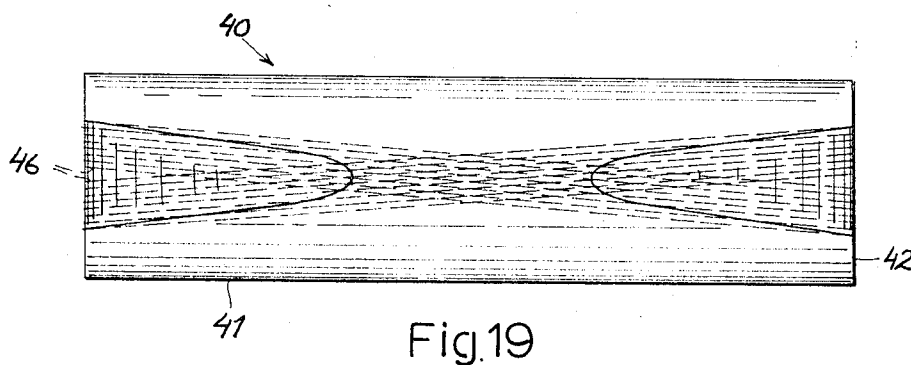
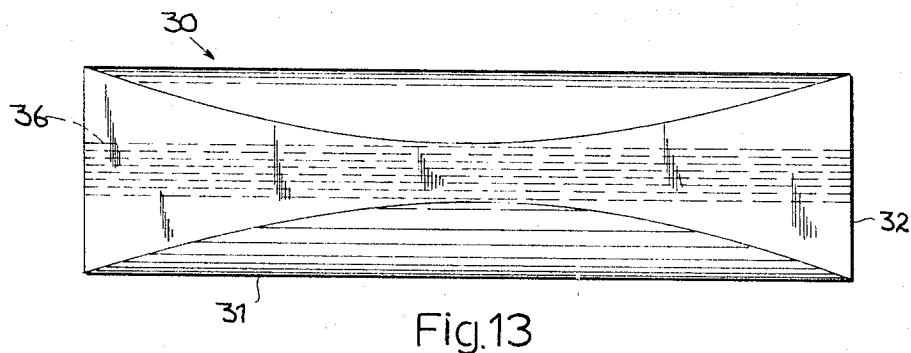
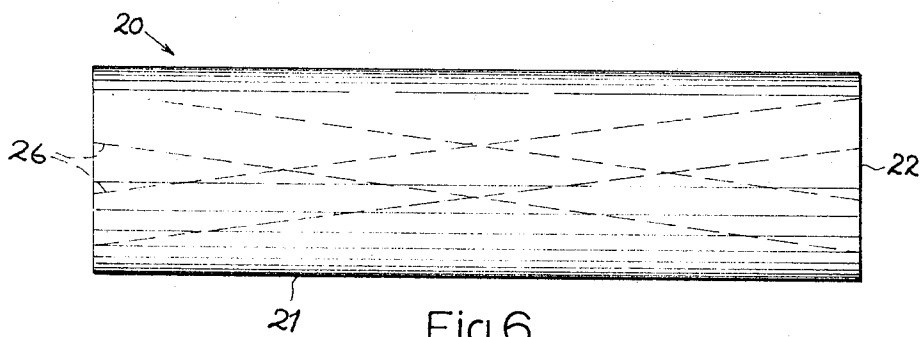
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SHELL STRUCTURE FOR CONCRETE CONSTRUCTION

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SHELL STRUCTURE FOR CONCRETE CONSTRUCTION

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4 Sheets-Sheet 4

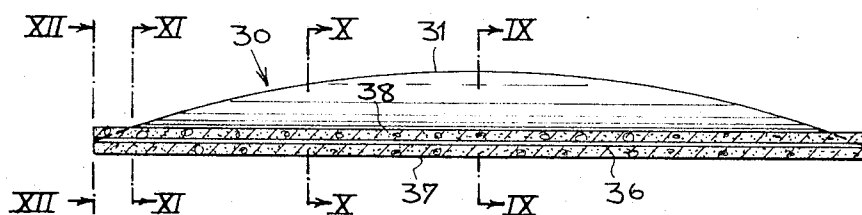


Fig. 8

Fig. 9

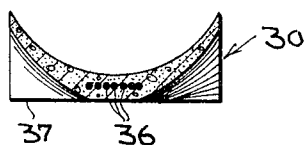


Fig. 11

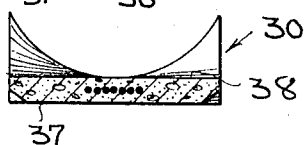


Fig. 10

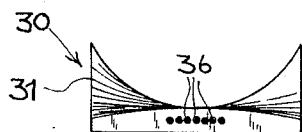


Fig. 12

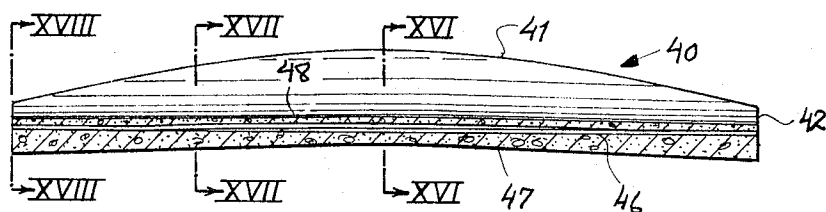


Fig. 15

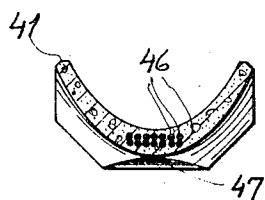


Fig. 16

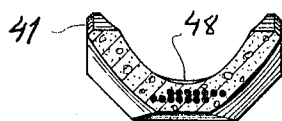


Fig. 17

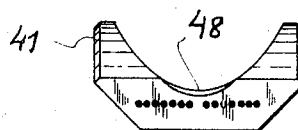


Fig. 18

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3,296,754 SHELL STRUCTURE FOR CONCRETE CONSTRUCTION

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Filed Nov. 22, 1963, Ser. No. 325,704
Claims priority, application Germany, Nov. 28, 1962, S 82,611
11 Claims. (Cl. 52—80)

Our present invention relates to a shell structure of the general type disclosed in our copending application Ser. No. 168,700, filed January 25, 1962, now Patent No. 3,142,136, issued July 28, 1964, i.e. a concrete shell of substantially rectangular horizontal outline and upwardly concave transverse curvature.

Heretofore, as more particularly described in our above-mentioned U.S. patent, such shells were preferably designed as bodies with negative Gaussian curvature conforming, at least approximately, to a one-sheet hyperboloid with straight-line generatrices extending substantially diagonally across the rectangle, the region of these generatrices representing a convenient site for the embedding of tensioned prestressing elements (e.g. steel cables) in the concrete. Other reinforcements, e.g. in the shape of suitably curved wires or rods without prestress, could be embedded close to the upper and lower surfaces of the shells.

Structures of this description, with a shell thickness of, say, 5–7 cm. or about 2–3", have been found satisfactory for use in various types of roof construction as disclosed, for example, in our copending application Ser. No. 133,754, filed July 21, 1961, now Patent No. 3,207,054 issued September 21, 1965, in which a plurality of such shells are disposed side by side on supporting walls or piers with interposition of curved connecting members such as plates of corrugated sheet material.

In these prior construction, the shells were generally of uniform thickness so that both their upper and lower surfaces had substantially the same approximately hyperboloidal shape. This configuration, while simplifying the task of the designer, imposes certain limitations upon the load-carrying capacity of the shell structure. To increase this capacity, it would be necessary to deepen the concave upward curvature of the shells, to increase their overall thickness and/or to enlarge their width. The first of these measures is only limitedly feasible because of manufacturing difficulties in the pouring of concrete shells whose sides slope upwardly at an angle greater than about 30° with reference to the horizontal. The increase in thickness is frequently objectionable in that it also adds to the weight of the shell itself, thus entailing not only higher costs but also a less favorable ratio of live to dead weight. The width of the shell, finally, is limited in the case of precast structures by considerations of transportation and handling.

The general object of our present invention is, therefore, to provide an alternate solution for the problem of increasing the load-carrying capacity as well as the stability of such shell structures.

A more specific object of our present invention is to provide a shell of such shape that its central zone, in which the prestressing elements are concentrated, will be strengthened without objectionable increase in overall weight.

It is also an object of our invention to provide a shell structure of the general type set forth which retains its load-carrying capacity and stability even when provided with a flattened underside at its supported ends (i.e. in the region of the minor sides of the rectangle) so as to be more conveniently deposited on building walls or other types of piers.

We have found, in accordance with this invention, that a substantial increase in the load-carrying capacity of an upwardly concave shell can be obtained by only a partial enlargement of the shell thickness, particularly in the central transverse zone, advantageously with a gradual change in shell thickness from the middle of its central cross-section toward the ends thereof. The increased thickness enhances both the shear strength and the bending resistance of the shell but, by being confined to selected locations, does not involve a commensurate increase in weight.

In principle, the change in thickness from the middle of the central cross-section to its ends may be either positive or negative, this cross-section thus assuming the shape of either a diverging or a converging meniscus. A shell with a diverging meniscus, i.e. with a generally bow-tie-shaped central cross-section, is claimed in our copending application Ser. No. 325,703, filed on even date herewith. The present disclosure is therefore specifically directed to shells whose upper surface has a larger radius of transverse curvature than its lower side, at least in the central region of the structure.

The increase in shell thickness along the central longitudinal plane lowers the center of gravity of the cross-section of the shell and effectively increases its stability. This lowering of the center of gravity, bringing it closer to the level of the geometrical center of the section as compared with shell sections of uniform thickness, also strengthens the outwardly directed transverse moments, or edge torques, which is desirable in the presence of strong contractile forces exerted in transverse direction, particularly in the region of the supports, by crossed tension members within the shell.

Since the shear stresses due to the supports tend to concentrate along the longitudinal axis of the structure, our present improvement enhances the shear-resisting capacity of the shell without proportionately adding to its weight.

Another possibility afforded by our present invention is the flattening of the underside of the shell, either throughout its length or only in the region of the supports. According to a further feature, the upper shell surface may also be flattened in such manner that the edges of the shell progressively converge toward the median plane upon approaching the supported sides, again with a concomitant gradual increase in the median shell thickness.

The several modifications referred to above afford a variety of choices for the disposition of the generally longitudinal prestressing elements. As long as the curvature of at least the upper surface approximates that of a one-sheet hyperboloid, the prestressing means may extend substantially diagonally as in the previously disclosed shells of uniform thickness. With a flat-bottomed shell, on the other hand, the direction of prestress may be parallel to the longitudinal edges, if desired. With hybrid structures, the prestressing elements may run at some intermediate angle. These elements may be constituted by various elongated elastic members, preferably of structural steel, e.g. in the form of one or more parallel cables or of flat ribbons.

The invention will be described in greater detail with reference to the accompanying drawing in which:

FIG. 1 is a perspective view of a shell embodying the invention, parts broken away;

FIG. 2 is a longitudinal sectional view taken on the line II—II of FIG. 1;

FIG. 3 is a side-elevational view of the shell shown in FIGS. 1 and 2;

FIGS. 4 and 5 are, respectively, a cross-sectional view and an end view taken on the lines IV—IV and V—V of FIG. 2 but drawn at a larger scale;

FIG. 6 is a bottom view of the shell shown in FIGS. 1-5;

FIG. 7 is a perspective view (parts broken away), similar to FIG. 1, of a modified shell embodying the invention;

FIG. 8 is a longitudinal sectional view taken on the line VIII—VIII of FIG. 7;

FIGS. 9-12 are cross-sectional and end views taken, respectively, on the lines IX—IX, X—X, XI—XI and XII—XII of FIG. 8;

FIG. 13 is a bottom view of the shell shown in FIGS. 7-12;

FIG. 14 is a perspective view (parts broken away) of still another shell embodying the invention;

FIG. 15 is a longitudinal sectional view taken on the line XV—XV of FIG. 14;

FIGS. 16, 17 and 18 are cross-sectional and end views taken, respectively, on the lines XVI—XVI, XVII—XVII and XVIII—XVIII of FIG. 15; and

FIG. 19 is a bottom view of the shell shown in FIGS. 14-18.

Reference will first be made to the structure of FIGS. 1-6. This structure comprises a concrete shell 20 of rectangular horizontal outline and negative Gaussian curvature with an upwardly directed concavity, the entire shell being upwardly cambered as best seen in FIGS. 2 and 3. The major sides of the rectangle are defined by a pair of upwardly arched longitudinal edges 21, its minor sides being constituted by edges 22 which are supported on piers 23 shown diagrammatically, in dot-dash lines, in FIG. 1.

The concrete of shell 20 is reinforced by steel-wire nettings 24 and 25, imbedded therein adjacent the lower and upper shell surfaces 27 and 28, respectively, and by prestressing elements in the form of two flat steel ribbons 26 which intersect at the center C of the shell and extend nearly diagonally across the rectangle. Each tensioned ribbon 26 may also be replaced, as illustrated in subsequent figures, by a bank of parallel cables numbering from one to about thirty or forty.

When seen in transverse cross-section, shell 20 has the invariable shape of a converging meniscus, or crescent, from its center (FIG. 4) to the supported ends 22 (FIG. 5). Thus, each transverse section of the shell is bounded by two nearly circular arcs, approximating sections of hyperbolas or parabolas, whose centers of curvature lie above the shell; the lower surface 28 has the smaller radius of curvature. The longitudinal edges 21 are of constant thickness from the center to the ends 22 and are parallel to the contours of the longitudinal midsection as seen in FIG. 2. In practice, the shell may have a minimum thickness of about 5 to 7 cm. at the edges 21 and a maximum thickness of about 10 to 15 cm. at its longitudinal axis, the preferred ratio of maximum to minimum thickness ranging between approximately 1.6:1 and 2:1.

The thickening of the median longitudinal zone of the shell lowers the center of gravity G of its transverse section, FIGS. 4 and 5, with reference to the geometrical center C thereof so that the distance d therebetween is considerably less than with structures of uniform thickness. The lower center of gravity G tends to give rise to outwardly directed transverse moments or edge torques M to counteract the inwardly directed forces created, particularly in the region of the piers 23, by the intersecting prestressing elements 26. Toward the midpoint of the edges 21 these torques are reduced, canceled or even reversed by transverse stresses due to the upward longitudinal camber of the shell 20.

Although the prestressed ribbons 25 have been shown twisted so that their ends are inclined to the horizontal, it will be apparent that their longitudinal axes (or the central element of an equivalent array of wires or cables) extend in a horizontal plane (if the slight deviation due to their intersection is disregarded) so as to define straight-line generatrices of an imaginary hyperboloidal

figure of revolution disposed between the upper and lower shell surfaces.

In FIGS. 7-13 we have illustrated a modified shell 30 with longitudinal edges 31 and transverse edges 32, defining a rectangular outline similar to that of shell 20 in the preceding figures. The central transverse section of the shell, seen in FIG. 9, is again substantially in the shape of a converging meniscus with generally hyperbolic curvature while being slightly flattened at the center of its convex side, owing to the presence of a flat bottom surface 37 which widens from the center toward the minor sides 32 so as to extend over the full width of the shell at the supported ends thereof. These ends, therefore, can rest on level-topped piers 33 (FIG. 7) representative of walls, beams, girders and the like, in contrast to the specially shaped piers 23 of shell 20 (FIG. 1). In the median longitudinal plane, as shown in FIG. 8, the lower and upper shell surfaces 37, 38 are both substantially horizontal so that the thickness of the shell remains constant along the median. The maximum thickness at the midpoint of the central shell section, seen in FIG. 9, again exceeds the minimum thickness at the edges 31 by a factor ranging between, preferably, about 1.6 and 2.

As will be apparent from FIG. 7, the transverse section of shell 30 changes from a crescent shape at the center to a plano-convex shape at the supported ends 32 so that the curvature of its upper surface 38 is inverted in the vicinity of these ends. The region of inversion, in which the surface 38 flattens out, is seen in FIG. 11. The wire nettings extending close to these surfaces and conforming thereto have been omitted in FIGS. 8-12 but the lower netting is visible at 34 in FIG. 7. Shell 30 also has prestressing means, disposed between these nettings, in the form of an array of rods or wires 36 of structural steel passing under tension along the longitudinal axis of the shell, this in a direction parallel to its edges 31; it will be apparent that the shell would also accommodate horizontal wires or the like disposed at a small angle to this axial direction. Naturally, the members 36 could also be replaced by one or more flat ribbons as in the first embodiment.

In FIGS. 14-19 we show a shell 40 whose longitudinally concave underside 47 flattens out toward the supported ends 42 (the supporting piers having been omitted in these figures) and which, in addition to unstressed steel-wire nettings (of which the lower one is visible at 44 in FIG. 14), incorporates prestressing means in the form of two sets of cables 46 that are inclined to the longitudinal axis at somewhat smaller angles than the ribbons 26 of FIGS. 1-6. The median shell thickness is again approximately constant, increasing but slightly from the center to the supported edges 42 in the plane seen in FIG. 15. In this longitudinal plane the top surface 48 is convex and substantially parallel to the concave lower surface 47; its transverse concavity, as shown in FIGS. 16-18, becomes progressively shallower and narrower toward the minor sides 42 or the rectangular outline, owing to a flattening of the edges 41 which thus broaden horizontally as they approach these sides. The result, as seen in the end view of FIG. 18, is a considerable increase in cross-sectional area at the ends, with corresponding strengthening of the shell in the region where the tensioned cables 46 (or equivalent ribbons) are anchored and the stresses due to the load are transferred to the supports. The central cross-section of shell 40 (FIG. 16) is similar to those of shells 20 and 30.

If the central transverse cross-sections of shell 20, 30 or 40 (FIGS. 4, 9 and 16) were given the shape of a diverging rather than converging meniscus, i.e. if the radius of curvature of the upper shell surface were made smaller than that of the lower surface in that plane, the center of gravity of this central shell section would rise. This would tend to intensify the inwardly directed edge torques and, while reducing the stability of the shell, would further increase its load-carrying capacity. An-

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other effect would be a shifting of the moment line of that section toward the compression flange thereof, i.e. toward the upper shell surface. This is advantageous in many instances in which it has been observed that, in the case of prior structures, the upper flange reaches its permissible limit of compression while the stresses within the lower flange are still well below the maximum tension allowed under the building code. Because of this rather unexpected phenomenon, shells of constant thickness do not always have a loading capacity commensurate with the tensile strength of the material, yet with shells of outwardly flared central cross-section this drawback is obviated through a redistribution of stresses so that both the compressive and the tensile strength of the concrete are fully utilized. This has been described in our aforementioned copending application Ser. No. 325,703, where such shells have been specifically claimed.

What is claimed is:

1. A structure adapted to be used in roof construction and the like, comprising a concrete shell of substantially rectangular horizontal outline with upwardly arched longitudinally edges at the longer sides of the rectangle, said shell being of upwardly concave transverse curvature at least over the major part of its surface and having a substantially crescent-shaped central cross-section, and reinforcing means imbedded within the body of said shell, said shell having a low center of gravity and being substantially free from edge torques in the region of said central cross-section.

2. A structure as defined in claim 1 wherein said shell is of substantially uniform transverse cross-section throughout its length.

3. A structure as defined in claim 2 wherein said shell is upwardly cambered in longitudinal direction.

4. A structure as defined in claim 1 wherein said shell has a flat underside at least in the region of the minor sides of the rectangle.

5. A structure as defined in claim 4 wherein said shell has flat upper surfaces extending inwardly from its longitudinal edges in the region of said minor sides.

6. A structure as defined in claim 4 wherein said flat underside extends substantially horizontally over the full length of the shell and widens from the center to said minor sides.

7. A structure as defined in claim 6 wherein said reinforcing means includes an elongated elastic member extending under tension substantially along the longitudinal median plane of the shell.

8. A structure as defined in claim 1 wherein said reinforcing means includes steel-wire nettings extending close

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to the upper and lower shell surfaces over the full length and width of the shell.

9. A structure as defined in claim 8 wherein said reinforcing means further includes at least one steel ribbon extending under tension in generally longitudinal direction between said nettings from one of the minor sides of the rectangle to the other.

10. A structure adapted to be used in roof construction and the like, comprising a concrete shell of substantially rectangular horizontal outline with upwardly arched longitudinal edges at the longer sides of the rectangle, said shell being of upwardly concave transverse curvature at least over the major part of its surface and having a substantially crescent-shaped central cross-section, and elongated prestressing means extending under tension in generally longitudinal direction from one of the minor sides of the rectangle to the other minor side within the body of said shell, said shell having a low center of gravity and being substantially free from edge torques in the region of said central cross-section.

11. A structure adapted to be used in roof construction and the like, comprising a concrete shell of substantially rectangular horizontal outline with upwardly arched longitudinal edges at the longer sides of the rectangle, said shell being of upwardly concave transverse curvature at least over the major part of its surface and having a substantially crescent-shaped central cross-section, and elongated prestressing means extending under tension in generally longitudinal direction from one of the minor sides of the rectangle to the other minor side within the body of said shell, the thickness of the shell varying between the middle and the ends of said central cross-section by a factor of substantially 1.6 to 2, said shell having a low center of gravity and being substantially free from edge torques in the region of said central cross-section.

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